VR AIDED CONTROL OF UNMANNED VEHICLES

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ABSTRACT

A new design for an immersive ground control station is presented that allows operators to monitor and control one or more semi-autonomous unmanned vehicles. This new ground station utilizes a virtual reality visualization of the operational space and the graphical representation of multiple real time information streams to create a comprehensive immersive environment designed to significantly enhance an operator's situational awareness and effectiveness. The environment simultaneously informs the operator about the position and condition of the vehicles under his or her control while providing an organizing context for the available information relevant to the engagement. This design is applicable to a range of vehicles including unmanned aerial vehicles (UAVs) and unmanned ground vehicles (UGVs).

1. INTRODUCTION

The complexity and capability of UAVs is expanding rapidly and the range of missions they are designed to support is growing. Currently, unmanned vehicles specialize in missions commonly categorized as "the dull, the dirty, and the dangerous" [1]. They have proven to be effective force multipliers that preserve the lives of military personnel. However, the DOD roadmap calls for unmanned vehicles to perform more missions and to be a larger part of our military force with fewer operators [1].

Significant technical challenges must be overcome for unmanned vehicles' potential to be reached. Many of these challenges are human interface issues, related to improving the systems used to monitor and control these vehicles. Chief among these challenges is to develop new mechanisms to expand the situational awareness of the operator beyond the level provided by current "soda straw" systems [2].

Additionally, the number of operators required to control an unmanned vehicle has to be reduced. Current methods require teams of operators for one vehicle. This has to be change so that one operator can control many. Coordinated advances in the vehicles and the command and control interfaces used to supervise them are required to accomplish this goal of group control.

The technology exists to create working prototypes for group control interfaces based on immersive synthetic visualization. Our work in this area is motivated by research in two related areas: the first in joint battlespace visualization, and the second in virtual reality (VR) aided teleoperation. The VRAC Virtual Battlespace integrates information about tracks, targets, sensors and threats into an interactive VR environment. Our VR aided teleoperation work successfully combines vehicle simulation, location tracking, and a virtual world representation to create a control station that provides superior situational awareness and control in the presence of signal lag. These two works can be combined to create a prototype future unmanned vehicle control station.

1.1 The Virtual Battlespace

In 2000, a research team at Iowa State University's Virtual Reality Applications Center (VRAC) began work with the Air Force Research Lab's Human Effectiveness Directorate and the Iowa National Guard's 133rd Air Control Squadron to develop an immersive VR system for distributed mission training called the Virtual Battlespace. The Virtual Battlespace integrates information about tracks, targets, sensors and threats into an interactive virtual reality environment that consolidates the available information about the battlespace into a single coherent picture that can be viewed from multiple perspectives and scales [3]. Visualizing engagements in this way can be useful in a wide variety of contexts including historical mission review, mission planning, pre-briefing, post-briefing and live observation of distributed mission training scenarios.

Knowledge gained from the development of the Virtual Battlespace

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **00 DEC 2004**	2. REPORT TYPE **N/A**	3. DATES COVERED -
4. TITLE AND SUBTITLE **VR Aided Control Of Unmanned Vehicles**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Virtual Reality Applications Center Iowa State University Ames, IA 50011-2274**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES **See also ADM001736, Proceedings for the Army Science Conference (24th) Held on 29 November - 2 December 2005 in Orlando, Florida. , The original document contains color images.**		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

contributed to the idea of creating a cohesive virtual world representing the status of real time and *a priori* information about an engagement [4]. Figure 1 shows the Virtual Battlespace environment displayed on a four-walled stereo projection system, the C4, at VRAC.

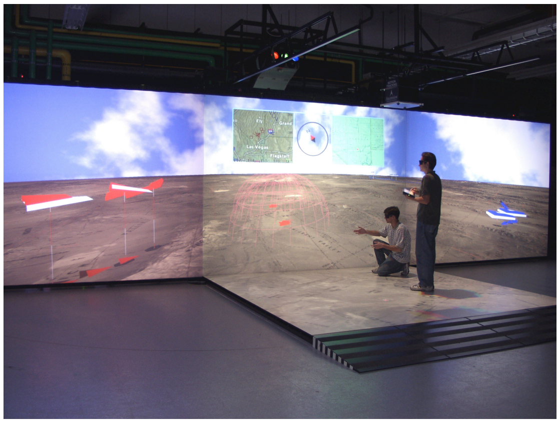

Figure 1. Battlespace Environment.

1.2 The VR-Aided Teleoperation System

In 2002, the same VRAC research team began work on a new teleoperation control system combining vehicle dynamics simulation, position and orientation tracking, and a virtual reality representation of the operational environment to create a vehicle control station that provides superior situational awareness and vehicle control in the presence of signal lag [5] [6]. The primary components of this VR aided teleoperation system are shown in Figure 2.

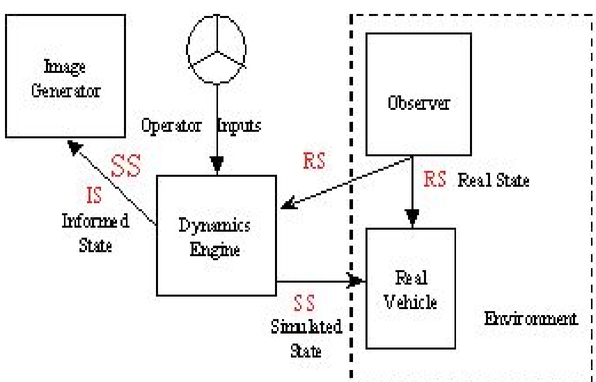

Figure 2. General System Model

The user controls the vehicle from a virtual environment displayed by the image generator using a vehicle buck. The operator's commands are sent to a dynamics simulation that uses these inputs to predict the dynamic state of the virtual vehicle. The dynamic state includes information such as position, velocity, acceleration and heading. The state created by the dynamics engine is a simulated state, used to both position the virtual vehicle and provide a desired path for the teleoperated vehicle.

The teleoperated vehicle receives these simulated states and synchronizes them to account for the lag and jitter generated by the communications delay. The vehicle uses these synchronized simulated states as goal states. A simulation run locally on the vehicle determines the inputs required to get the vehicle to approach the simulated state from its current state.

Of course, to calculate these inputs, the current state of the vehicle must be determined. A tracking system or observer provides this state information. The observer is responsible for reporting the vehicle's state information to the dynamics engine and the remote vehicle. The dynamics engine uses the reported vehicle position, corrected for lag and subsequent vehicle control, to predict the likely future position of the vehicle. As shown in Figure 3, this predicted position is depicted graphically as a wire-frame box surrounding the virtual vehicle that grows with the difference between the simulated state and the vehicle's projected state.

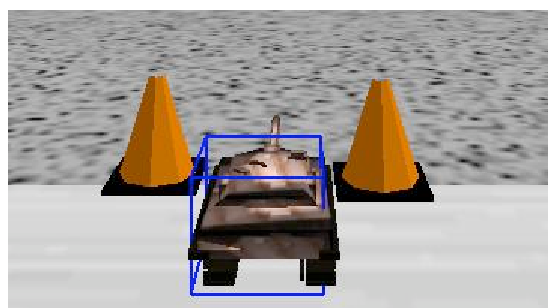

Figure 3. Wire-frame Envelope.

This wire-frame envelope allows operators to adjust their control to obtain higher fidelity with the remote vehicle, closing the loop between the operator and the vehicle.

1.3 Prototype Test Results

In order to test the effectiveness of the VR-Aided teleoperation system, our research team developed a prototype. In this test, the teleoperated vehicle was a remote controlled model tank. Our research team developed a custom circuit to allow the tank to be computer

controlled. The tank's response to controls was measured to create a computer simulation of the tank's dynamics and response to inputs. Once our team honed this simulation model, the tank's response to inputs could be closely predicted. The computer running this simulation (the dynamics engine) was a Dell PC attached to a Microsoft Sidewinder steering wheel set. The dynamics engine used the tank simulation to generate the simulated states (shown in Figure 2) and then sent those states to the laptop communicating with the RC tank.

Our team implemented an optical tracking system to act as the observer. A red cardboard square was placed on the top of the tank towards its rear and a blue square towards its front. A webcam, situated at a fixed location above the operational environment, produced a video stream. An image processing algorithm was implemented to find the blue and red squares in the scene. Calibration of the camera enabled conversion of the vehicle's marker pixel location into the corresponding location in the operational environment. Incorporating the fixed distance between the vehicle markers and the center of the tank, the system could determine both the tank's real-world position and its heading. Further, by keeping track of the previous position and orientation of the tank, the system could provide a first order approximation for the vehicle's linear and angular velocity. This information comprised the real vehicle state required by the vehicle and the dynamics engine (shown in Figure 2). The observer was run by a laptop and it communicated the vehicle state information via standard network protocols.

The image generator (shown in Figure 2) was an SGI RealityEngine2. It received simulated and real vehicle states from the PC and laptop respectively and generated the virtual world (shown in Figure 3). VRAC's C6 device displayed the virtual world in a 10 foot by 10 foot room where each wall is capable of displaying a rear projected stereo image. In this way, the system immersed the user with 3D stereo graphics in every viewing direction. Inside the C6, our team placed a steering wheel and chair. From this position the operator controlled the vehicle in the virtual environment.

All of the components of the test system were connected on the same low latency network. However, this does not reflect a typical operating environment where there is a significant signal delay between the vehicle and the operator. To simulate this crucial effect, each command sent by the operator to the vehicle was delayed before being transmitted. Likewise, information returning to the simulation from the vehicle observer was delayed. In this way, simulated signal delay was introduced into the system. Of course constant signal delay is not sufficient to model real world behaviors. To simulate variable delay, random perturbations in the delay times were introduced by fluctuating ±10% around the input median value.

To manage the changing signal delay times, operator commands were buffered at the vehicle, to ensure that they could be properly spaced in time. Buffering is a common technique used in multimedia systems to ensure smooth playback. Client-based players of streaming media on the internet typically buffer a portion of the song or video before it is played so that the next frame is available in time despite unpredictable signal delay. Smooth playback of the commands allows the remote vehicle's onboard computer to more accurately follow the simulated path that the operator generated.

To test the system, the tank was piloted through a course of cone gates within the operational environment using three methods: direct control, camera-aided teleoperation and virtual teleoperation. For each method, the average time to complete the driving task and the number of gates successfully navigated were recorded. Direct control provided the baseline for vehicle control because it is in some sense optimal; there is no signal delay and the operator can see the vehicle directly within its operational environment. Camera-aided teleoperation provided an important benchmark because it represents the most common current interface for teleoperated vehicles. Test runs were performed by the authors for all three control methods with three levels (one, five, and ten seconds) of nominal artificial signal delay. Table 1 shows the tests that were run. Our team measured the average time to completion and the number of cone gates successfully navigated. While our team did not run enough tests for a rigorous statistical analysis, initial results are promising.

These preliminary results reveal that the VR-aided teleoperation system greatly improved operator performance when compared to a lagged video-based teleoperation system. With VR-aided teleoperation, the average time to

completion was not noticeably affected by signal delays up to 10 seconds. In contrast, the camera aided teleoperation system completion times increased rapidly with only a modest increase in signal delay. Furthermore, the situational awareness of the operator was enhanced as evidenced by the fact that fewer cones were knocked down with VR-aided teleoperation.

Table 1. Test Results

Test	Signal Delay (s)	Average Time (s)	Average Cones Navigated
Direct	0	26.0	5.00
Camera	1	101.1	4.67
Camera	5	357.7	4.33
Camera	10	583.5	4.33
VR	1	32.5	4.67
VR	5	34.7	5.00
VR	10	31.0	4.67

2. FUTURE UAV/UGV GROUND STATION

A next generation unmanned vehicle (UV) control station must fill multiple roles. The system must provide a comprehensive view of the overall mission. It must clearly depict the mission context, including all the relevant geographic and political features of the area in which the unmanned vehicles are being operated. Further, it must show the position of all the UVs in the area. If a group of vehicles is acting in concert as a swarm, the intent of the swarm must be clear. This same system must also allow an operator to understand the detailed status of an individual UV and afford rapid access to the information necessary to make specific, decisive and informed decisions about its behavior. This means that whatever information sources are used in the control of a single UV must also be present in a system that controls many.

A system that employs a virtual environment as the information focus is an excellent candidate to solve these challenges. A large scale VR display is more versatile than current 2D desktop interfaces because it can fuse information from several sources into one comprehensive picture due in part to its increased display area. This frees the user from having to mentally integrate information displayed in different locations. A virtual world can create an integrated view of the mission by combining views from onboard cameras with the radar-derived positions of enemy, friendly, and unidentified tracks. In contrast, current UV control stations present all information feeds - on-board cameras, radar, sensor data and time history radar (tracks) - in separate displays. The operator must take on the integration task, significantly increasing his or her cognitive load.

Our team defines VR control as a system that uses a virtual world as the UV control interface. A requirement for VR control is to generate virtual terrain that can provide meaningful context for a given mission. This terrain model can be a composite that fuses satellite imagery, political boundary maps, DTED data and other sources. The obstacles to creating useful terrain models are not unreasonably high for UAVs. Since only general landmark features are necessary to fly a UAV, the terrain model need not match every contour of the real terrain to be effective. As a result, virtual terrain for VR control can be implemented for current generation UAVs.

VR control is harder for UGVs than UAVs. The main reason is that the obstacles to creating useful terrain models are higher for UGVs. To facilitate ground control, a terrain model must incorporate higher frequency detail to accurately simulate the motion of a UGV. Real time onboard terrain generation using laser range finders might be needed for VR control to be effective for UGVs. However, future UGVs are likely to be semi-autonomous with advanced sensors, requiring only that the operator lay out a path for the vehicle instead of driving it. Under these conditions, the terrain can be less exact, making UGV VR control easier to implement.

With VR control we expect the operator to feel a greater sense of presence and to have a more complete understanding of a UV's situation than is possible with traditional 2D desktop displays. The virtual world can be as accurate a representation of the real world as current desktop displays are now. Radar feeds can be used to position units, GPS can be used to pinpoint UVs in the swarm, weather data from balloons and satellites can be used to generate the weather in the virtual world, and camera feeds can be used to update visuals of the targets. The difference between current systems and VR control is that all of this information can be integrated into a comprehensive view, rather than displayed in a fragmented way.

Signal lag, a problem in conventional video-based UV control systems, also complicates VR control because each piece of

information required to accurately represent the elements in the virtual world is affected by lag. Signal lag can be critical in the heat of combat and in accurately hitting targets [7]. This lag effect is not unique to VR control -- lag is always be present in any UV control system. However, using VR control provides a key advantage in minimizing the effects of lag. The VR environment provides us with the ability to modify the virtual UV's positions in the virtual world dynamically using informed or dead reckoning [5]. Reckoning a position provides an estimate of a vehicle's true, unlagged position. If the display does not use a reckoned position for the vehicle, the operator is essentially attempting to operate the UV "in the past". Reckoning vehicle positions can help to alleviate the effects of lag by allowing the operator to control the UV not in its past, but in its likely, but unknowable, present state [5].

3. VR CONTROL PROTOTYPE

We have developed a prototype for VR control of UVs based on the Virtual Battlespace. The prototype has two main modes, far scale and close scale. It can also direct operator attention with alerts and place video feeds "in situ" within the virtual world to provide organizing context.

3.1 Far Scale

Far scale allows an operator to survey the overall mission from a strategic viewpoint above the engagement. In this mode, the virtual world is used to display most or all of the units involved, both friendly and enemy. The operator uses this view to get a sense for the overall mission. This view is crucial for managing multiple UVs because it provides an organizing context for the engagement and displays spatial relationships between UV swarm elements.

In far scale, the operator is situated thousands of feet in the air with a comprehensive view of the battlefield and its participants. Individual units can be aggregated, if appropriate, into squads to simplify the visual clutter by representing them as single entities. Figure 4 shows the view of a battle over a simulation of the test range at Nellis AFB in Nevada in far scale; the red and blue wedges represent aggregated aircraft. Colors represent the allegiance of the units, with red representing hostile and blue representing friendly units.

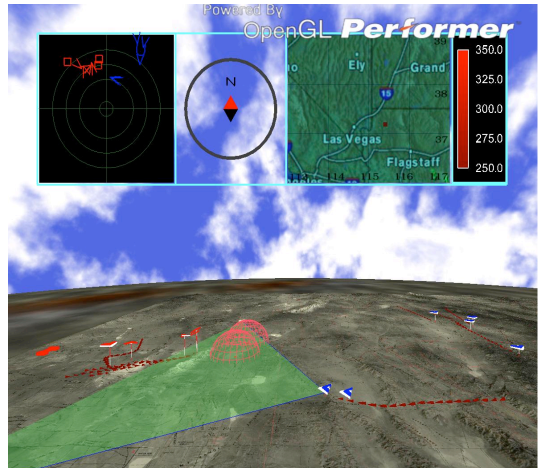

Figure 4. Far scale.

Figure 4 shows other valuable information that the operator has access to in far scale. The green wedge in front of the blue aggregate unit in the middle of the screen represents the extents of the squad's radar sweep. With this information, the operator knows exactly which units that squadron's radar can detect. This knowledge is useful in determining when a squadron can be expected to acquire its target.

The units in far scale can leave trails behind them, represented in the virtual world by a red dashed line. The trails tell the operator where units have been and provide a context for tracking overall movement. Potential SAM threats are represented by pink wire frame hemispheres (located at the top far edge of the green radar sweep wedge). Aircraft which fly within this zone are in danger of being targeted and shot down; ground forces in this zone must contend with the SAM ground protection forces.

Other sources of information in the far scale can be displayed on the two-dimensional billboard located at the top of the screen in Figure 4. The billboard contains a traditional radar display, a compass, a map showing current geographical location, and a speed key. This speed key can be used to determine the approximate speed of a unit by its color. The other very important piece of information this view provides is the relative spatial relationship between terrain, units and threats. It is this facet of the virtual world that allows it to provide superior situational awareness.

3.2 Close Scale

The system's second mode, close scale, allows an operator to view a mission from the perspective of a single unit. Close scale provides a more detailed view of a portion of the mission space. Many times an operator would like to get a more complete view of what is occurring near a particular unit. This is especially true for tasks like target confirmation or direct control. For these tasks, the operator switches to close scale mode, allowing him or her to follow closely behind a particular unit. Realism is enhanced in close scale by representing the vehicle with detailed unit models. Figure 5 shows close scale.

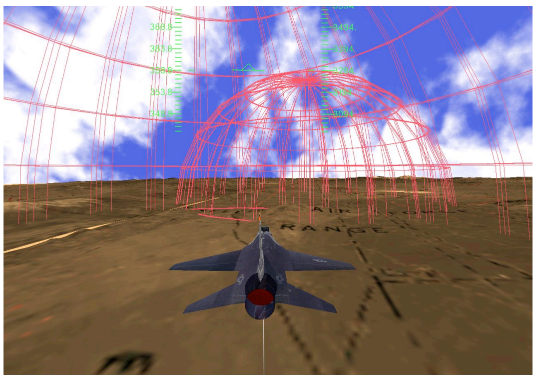

Figure 5. Close scale.

Note that in Figure 5 the aircraft of interest, an F-16, is flying through a threat dome of a SAM site. The environment provides information to the operator about immediate danger to the aircraft as well as how far that danger extends. Aircraft specific information is displayed on a simulated heads up display (HUD) showing heading, altitude and speed. Another graphical feature, available in both scales but more critical in close scale, is height sticks. These are poles attached to aircraft that extend vertically downward to the ground and are striped to give a quick estimate of altitude. They are highly visible and can cue the operator to the presence of other aircraft in the area that would otherwise be undetectable at this scale. Ground vehicles are also marked with a stick to make their locations visible.

If the vehicle of interest is a UV, the operator could use this scale to control the vehicle directly, using the VR-aided teleoperation control model described in the tank simulation above. An operating envelope similar to the one shown in Figure 3 could be integrated in the virtual world to provide the operator with feedback about uncertainty in the current position of the vehicle. With this control capability, an operator would be able to rescue a UV from a situation that its own control system was unable to handle. A key question for us is how effective a single operator can be at managing the state of several UAVs in a swarm using these two scales. A partial answer to the question is provided by alerts.

3.3 Alerts

If one of the UAVs in the swarm requires attention or intervention, it must alert the operator. An alert attracts the operator's attention, by raising a cue either graphically, orally, haptically, or in combination. In response to an alert, the operator can switch between scales manually or the system could be configured to transition automatically. Figure 6 shows what an alert might look like in far scale.

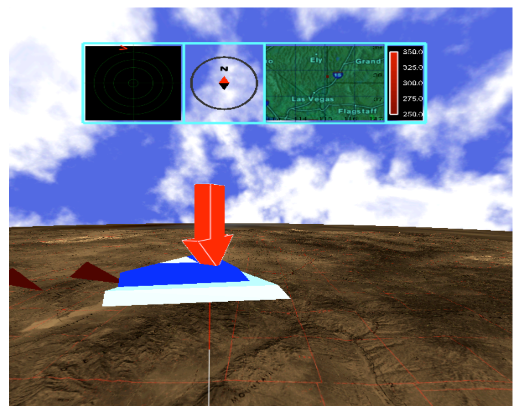

Figure 6. UAV alert in far scale.

An alert in close scale could be a flashing arrow pointing in the direction of the UAV in need. We are exploring several possible alerts. For example, if an alert happens while the operator is attached to a different unit in close scale, the application could seamlessly switch to far scale to give the operator a global view of the battlefield. Alternatively, the system could seamlessly move the operator from his current focus of control to the unit that raised the alert. The key concept in how alerts and the two scales work together to allow swarm control is that the far view provides an overall but less specific view while close scale provides a narrow but highly focused view. The alert system helps guide the operator's attention to the parts of the engagement in which it is most needed. The two scales in concert with alerts create a control environment conducive to distributed command of semi-autonomous vehicles. We believe that

the environment will help alleviate the losses in situational awareness that cause human operators to make mistakes.

3.4 "In Situ" Video

One of the most important features of a UV control station is the capability to view the UV's video feeds. As well as being today's primary basis for vehicle control, in the case of reconnaissance missions, real time video is the most important information the UAV gathers. Today's systems display UAV video feeds on separate monitors, or within individual windows in a desktop environment. This interface offers limited contextual information for the video and as a result, the operator must mentally position the video within the mission context, augmenting the on-board camera's limited field of view. This limited view contributes significantly to the loss of situational awareness [8].

In the VR based system, video is still an important information source. In its simplest form, video from a UV can be played on a billboard display, as shown in Figure 7.

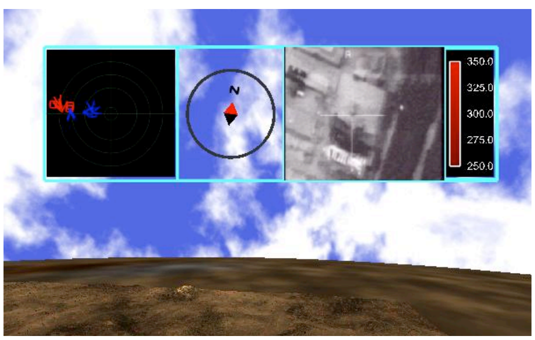

Figure 7. Video feed in a fixed location.

While playing video on a billboard within the environment does fuse the virtual world with the real time sensor feed, it is similar to current display systems in that it requires the operator to provide the video's context. An interesting alternative is to place the video "in situ", fusing the video image in place with the rest of the virtual world to provide the missing contextual information. In this mode, video from a UV feed is superimposed in its correct position within the virtual environment, either by texturing the terrain, in the case of a ground directed camera, or on a "suspended screen" in the case of an on board camera. With "in situ" placement, an operator can easily place video information in context. Furthermore, contrast between the terrain shown and the virtual terrain it replaces can provide information about how accurately the virtual terrain matches the actual terrain. "In situ" video placement in the virtual world allows the operator to confirm the vantage point that the video is taken from, rather than having to infer it from pre-briefing information or by integrating information from other displays. Figure 8 shows an example of an "in situ" video taken from a UAV.

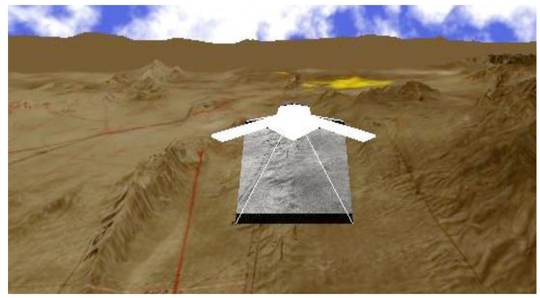

Figure 8. Video feed in a fixed location.

A further method to introduce video into the scene is to lay the images coming from a UAV along the vehicle's flight path while in far scale. Using this method, the video stream can be used to generate a dynamic ground texture that contains the latest information available from the UAV camera. For example, if an operator wished to look at what the UAV "saw" when it passed over a particular mountain range, he or she could navigate to that mountain range in the virtual world and select the video strip on the UAV's flight path at that location.

NASA pioneered path specific video placement with their virtual environment vehicle interface (VEVI) for the Mars Pathfinder Mission [9]. The VEVI system used these videos for review of mission data, not control of the vehicle. VEVI is shown in Figure 9.

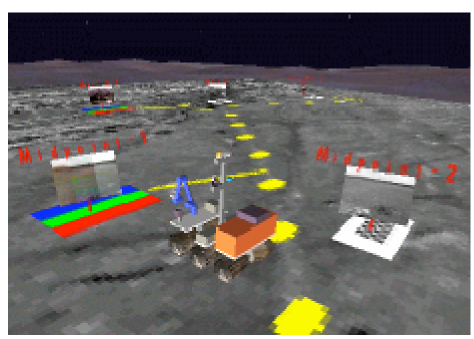

Figure 9. VEVI Interface.

Each of the video clips in Figure 9 is displayed over the point on the Martian

landscape where the clip was taken. If a scientist wants to review what the Pathfinder saw at a certain location, he simply selects the video clip closest to that location and plays it. VEVI demonstrated that “the ability to continually see all around the robot provided scientists with a more natural sense of position and orientation … than is usually available through more traditional imaging systems” [10]. The authors also note that “this capability … substantially accelerated site exploration” [10]. We are apllying this same “in place” philosophy to UV control to allow the operator to quickly locate and review footage from the UV’s camera, either from the past or in real time.

In order for a single operator to successfully control multiple UVs he must constantly juggle his attention from one UV to another, have all the needed information displayed in one location, and understand the relationships between the UVs under their control, as well as potential targets and threats. A virtual environment that uses camera feeds to augment the virtual battlefield can accomplish all of these tasks in a way that is flexible and extensible. Since most of the complexity is in software, new ways to represent the information can be implemented quickly to respond to new technology and user requirements.

4. CONCLUSION

The Department of Defense has allocated $2.8 million in the 2005 defense appropriations bill to fund research in virtual teleoperation for unmanned vehicles at VRAC. The goal of this research effort is to develop VR based technologies to create control and monitoring interfaces that work toward the DOD Roadmap's goals for simplifying the command and control of groups of unmanned vehicles in a variety of missions [1]. The core of our approach is a synthetic *a priori* virtual model of a mission space that incorporates dynamic elements whose representations within the virtual space are driven by real-time, or near real-time, sensor feeds. Our goal is to identify and solve the problems associated with using this virtual environment to monitor and operate unmanned vehicles in a variety of missions and identify the appropriate connections between this research and other research in the unmanned community.

The research group at VRAC is actively seeking industry and defense agency stakeholders who can help guide and focus this effort and help identify the most crucial points of integration. In keeping with Iowa State University’s land grant mission, we maintain a strong commitment to identifying mechanisms for effective technology transfer of results of this research to make a positive impact on the operation of these vehicles in the real world.

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